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Part 2. Applications

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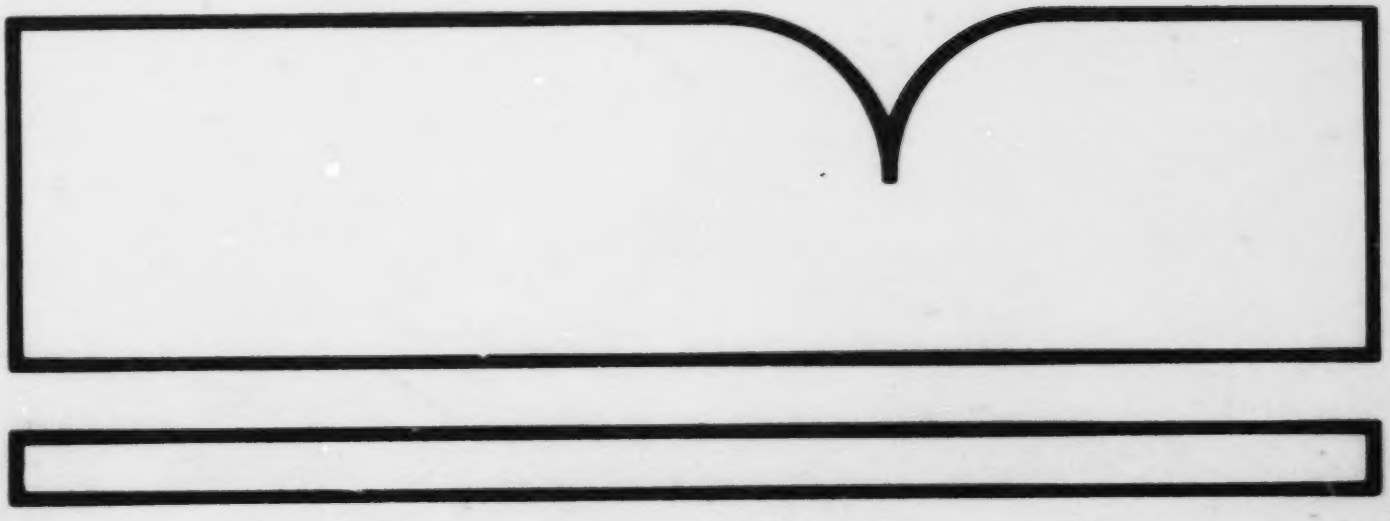

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16. ABSTRACT

The objective of this paper is to provide an example of the application of personal computers for water quality management in Green Bay, Wis. The capabilities of the personal computer can help decision makers determine the level of remediation necessary to meet specified water quality goals through: development and use of complex mathematical models for water quality parameters, such as phosphorus and oxygen; organization and manipulation of the large amounts of field data required for model calibration and verification; simulation of a variety of management options aimed at cost effective improvement of water quality, and effective communication of technical concepts and management recommendations to decision makers and public interest groups.

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Personal computers and environmental engineering

Part II - Applications

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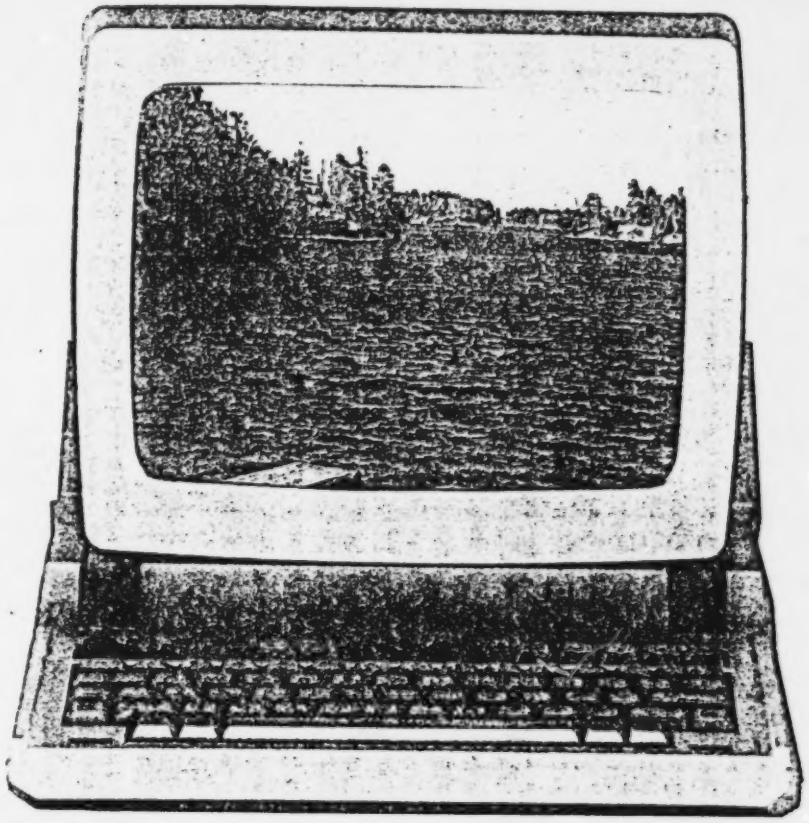

Dramatic advances have been made in micro or personal computer technology in recent years (*1*). Most environmental engineers now have direct access to such computers and are using them increasingly because of their low cost and ever-expanding capabilities. Personal computers also are portable and easily programmable for graphic and animated displays.

There are, however, significant questions regarding the role of personal computers for large-scale water quality management applications. For example, mathematical operations and data handling processes are slower on personal computers than on traditional mainframe computer systems. If this limitation of the personal computer is not too serious, we may be able to increase significantly our ability to communicate the results of technical analyses to decision makers. However, if the characteristics of personal computers prove too limiting, we may be unable to perform calculations efficiently.

The objective of this paper is to provide an example of the application of personal computers for water quality management in Green Bay, Wis. The capabilities of the personal computer can help decision makers determine the level of remediation necessary to meet specified water quality goals through

- development and use of complex mathematical models for water quality parameters, such as phosphorus and oxygen,
- organization and manipulation of the large amounts of field data required for model calibration and verification,
- simulation of a variety of management options aimed at cost-effective improvement of water quality, and
- effective communication of technical concepts and management recommendations to decision makers and public interest groups.

The Green Bay system

Green Bay, a large gulf on the northwest corner of Lake Michigan, has been cited as one of the major problem areas for water quality in the Great Lakes. The bay's length along its major northeast-southwest axis is 160 km, its mean width is 22 km, its mean depth is 15.8 m, and its mean hydraulic residence time is six years (*2*). The four major tributaries to the bay are the Fox, Oconto, Peshtigo, and Menominee rivers. The Fox River, which is the largest source of water and pollutants, contributes 45% of the major tributary flow and 63% of the tributary biochemical oxygen demand to Green Bay. It also discharges 78% of the total phosphorus and 87% of the suspended solids loads into the bay.

Marked longitudinal gradients in water quality and trophic state occur along the major axis of the bay in response to pollutant loadings from the Fox River. The southern end of Green Bay is hypereutrophic: It contains high levels of turbidity, chlorophyll, and phosphorus and is not saturated with dis-

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solved oxygen, despite its shallow depth. Water quality improves with distance from the mouth of the Fox River, approaching an oligotrophic state approximately 100 km to the north, near the bay's junction with Lake Michigan.

Historically, industrial (pulp and paper), municipal, and agricultural discharges of oxygen-demanding substances and nutrients that stimulate algal growth have contributed to severe depletion of dissolved oxygen during the summer in the lower Fox River and southern Green Bay. In winter, oxygen depletion has occurred under the ice to a distance of 25 km along the east shore of the bay (*3*). Reductions in point source loads of oxygen-demanding substances during the past decade have led to some improvement in water quality in the Fox River and southern Green Bay (*4*).

Nevertheless, significant residual water quality problems remain. These problems are related to point and nonpoint sources of phosphorus and sediment as well as internal production of oxygen-demanding materials. Green Bay waters exhibit poor transparency because of excessive levels of phytoplankton and abiotic particulate matter. Severe hypolimnetic oxygen depletion has been observed at eutrophic and mesotrophic mid-bay sites far from discharges of organic material, apparently in response to nutrient enrichment (manmade eutrophication). Remediation efforts are hindered by both the severity and the complexity of the problem.

In this article, we will describe a mathematical model designed to clarify cause–effect relationships between pollutant loads and environmental conditions in Green Bay. The model is used to simulate the impact of remedial actions on water quality.

Purpose of the computer program

The computer program was designed to:

- orient the user and communicate the overall features of the study site and approach;
- provide the capability to store and retrieve large amounts of information, including field data, model coefficients, and forcing functions;
- compute interactively pollutant concentrations on both a steady-state and dynamic basis in all parts of the bay; and
- provide an interactive management analysis tool for decision makers to permit convenient evaluation of alternative pollution abatement plans.

Definitions of symbols in Equation 1

A_i = area of the interface between i and the adjacent cell j
C_i = the oxygen concentration in cell i
C_j = the oxygen concentration in adjacent cell j
C_s = the saturation oxygen concentration
E_i = the coefficient for dispersion across the boundary of cell i
K_i = the atmospheric oxygen exchange coefficient for cell i
L_i = the distance between the centers of cells i and j
P_i = photosynthetic production of oxygen in cell i
Q_i = the flow leaving cell i
Q_j = the flow entering from cell j
R_i = water column respiration in cell i
S_i = sediment respiration in cell i
t = time
V_i = the volume of cell i
W_i = the tributary oxygen loading to cell i

TABLE 1
Source and sink terms for the water quality mass balance model

Variable	Source	Sinks
Chloride	Tributary loads	None (conservative)
Total phosphorus	Tributary loads	Settling
	Atmospheric loads	
	Sediment release	
Total organic carbon	Tributary loads	Settling
	Primary production	Water column respiration
Dissolved oxygen	Atmospheric exchange	Atmospheric exchange
	Photosynthesis	Water column respiration
		Sediment respiration

The mass balance model

Water quality conditions in Green Bay are simulated using a mass balance model. The bay is divided into 19 control volumes or model cells (12 surface cells—one for each surface cell that exhibits thermal stratification—and 7 bottom cells). A mass balance computation is performed on each model cell for all the variables of interest, such as chloride, total phosphorus, total organic carbon, and dissolved oxygen. The mass balance includes exchange among adjacent model cells (horizontal and vertical mass transport) and all sources and sinks of material (Table 1). The last three variables in Table 1, phosphorus, organic carbon, and oxygen, are closely related. The phosphorus concentration controls algal activity and the internal production of organic carbon. The breakdown of organic carbon in the water column and in sediment has an impact on the dissolved oxygen mass balance.

The general form of the mass balance equation for oxygen in each model cell is given in Equation 1:

$$V_i \frac{dC_i}{dt} = \sum_j \left[\frac{E_i A_i}{L_i} (C_j - C_i) + Q_j C_j \right] + W_i - Q_i C_i + K_i(C_s - C_i) + P_i - S_i - R_i$$

The terms that appear in Equation 1 are defined in the box. Similar equations are developed for all of the other dependent variables, such as chloride, total phosphorus, and total organic carbon. Variable-specific source and sink characteristics of these materials are accounted for in the equations. The equations are solved either as a function of time or at steady state ($dC_i/dt = 0$).

The geometry of each cell (A, L, V) was calculated using data for the shape and depth of the water body obtained from National Ocean Survey charts. Sources, sinks, and mass transport characteristics were quantified through an extensive program of field-monitoring and laboratory experimentation. Tributary loads (W) were calculated from river water chemistry data and U.S. Geological Survey (USGS) flow records. Algal production of oxygen and organic carbon was calculated by relating photosynthesis (P) to light, temperature, and phosphorus concentration (*5*, *6*).

Water column respiration (R) was found to be a linear function of the total organic carbon concentration. Sedi-

ment respiration (S) was calculated ... artificial sediment characteristics ... laboratory measurements of sediment oxygen demand (*7*). Re-aeration was calculated as the product of the atmospheric exchange coefficient (K) and the surface water oxygen deficit (*8, 9*). Net horizontal advective mass transport (Q) was calculated as throughput using tributary flow data (USGS). Dispersive mass transport (E) was estimated from chloride profiles (horizontally) and from temperature profiles (vertically) (*10*). Data for overall model development were collected weekly at 34 bay and tributary stations from May to September 1982.

The model of the Green Bay system has several components and includes complex nonlinear interactions and processes. The overall model contains 114 differential equations with time-variable forcing functions. These equations must be solved numerically. The field data set for model calibration contains approximately 8000 individual items of information. We need to be able to manipulate these data easily and quickly. Finally, we would like to perform simulations rapidly and interactively to encourage application of the model for decision making. Computer software that meets all of these needs has been developed for this study and is described below.

Applying the models

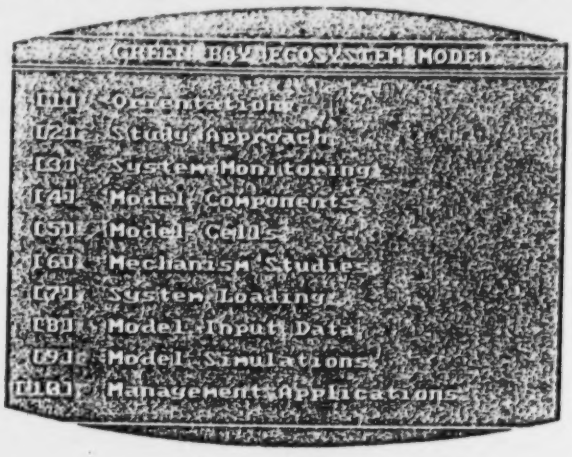
The complexity of the water quality problems and the management issues facing decision makers in Green Bay must be addressed through the development and application of mathematical models. The models described here are based on an extensive field-monitoring program and analyses of the key physical and biochemical processes that influence water quality. The potential of the personal computer for communicating results and facilitating the decision making process was examined using a comprehensive computer program written for the IBM PC in the BASIC language.

The program is menu-driven to facilitate use and provide flexibility of operation. The main menu for the model software is shown in Screen 1. This, along with other color figures in this paper, are photographic images of the actual computer screen.

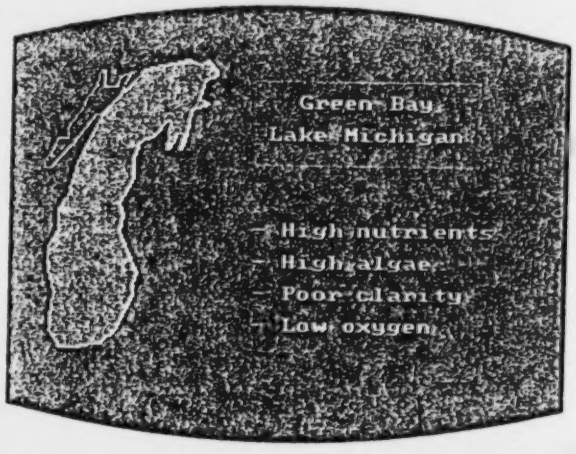
The main menu allows the user to select any of 10 options, ranging from an orientation and outline of the study approach to management applications. Thus all of the components of a comprehensive water quality management tool are at the fingertips of the user in a single personal computer program.

System familiarization. The first five options from the main menu

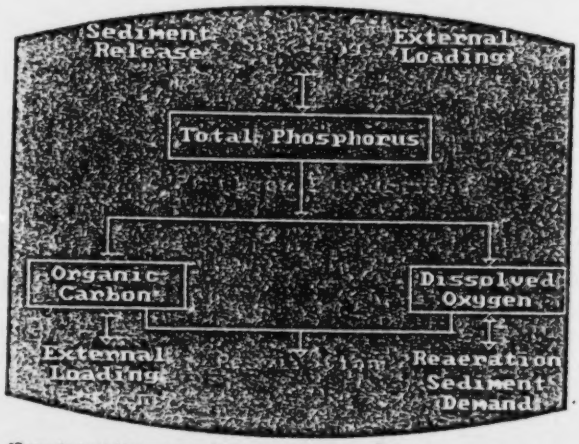
SCREEN 1
Main menu for Green Bay ecosystem model software



SCREEN 2
Listing of some water quality problems and site location for Green Bay and Lake Michigan



SCREEN 3
Key components and processes in the model*



*Dependent variables are shown in red; calculated variables in yellow; and loading, kinetic, and mass-transfer processes in green.

(Screen 1) are concerned with system familiarization. They provide the user with an idea of the general nature of water quality problems in Green Bay, the structure and components of the model, and the location of monitoring stations. Screen 2 shows a computer-drawn map of Lake Michigan and Green Bay and a list of some important water quality problems. Color graphics enhance communication and increase the interest of users. This is one of the chief advantages of using personal rather than mainframe computers.

Option 4 from the main menu (Screen 1) gives a submenu that allows the user to view the overall interactions among the model components and examine the details of any single variable in the model. Screen 3 shows a computer-generated color graphic representation of the key components and interactions in the model. Different colors are used to distinguish between dependent variables, internally computed variables, forcing functions, kinetic processes, and mass transfer mechanisms. Dependent variables are shown in red; calculated variables in yellow; and loading, kinetic, and mass transfer processes in green.

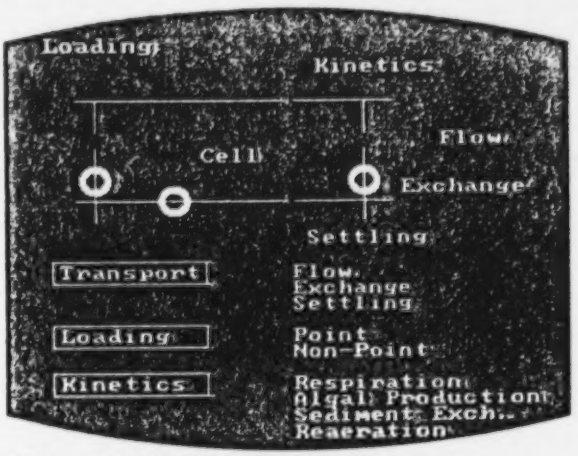
This illustration is constructed piece by piece as the user displays each component of the model using keyboard commands. Thus the presentation of these ideas is comparable to an artist's dynamically painting a scene rather than a photographer's snapping a static picture. We believe the ability to construct such a graphic rather than simply to show a completed illustration leads to more effective communication. The personal computer and the color graphic screen provide an ideal means of using this approach.

Screen 4 shows the processes that occur in a single model cell. This figure is constructed by the computer with color graphics and uses animation to illustrate turbulent exchange among model cells. Animation is accomplished by slowly revolving the concentric circles that represent the exchange process. This simple technique helps communicate complex ideas to decision makers who may not always be familiar with the technical concepts. Screen 5 expands these ideas to show how cells in a network interact. The circles and arrows move to represent the mass transport process.

Screen 6 shows a computer graphic of the model cells superimposed on a map of the Green Bay, along with sampling stations in the bay and in its tributaries. These types of illustrations facilitate rapid and effective communication between the engineer and the decision maker.

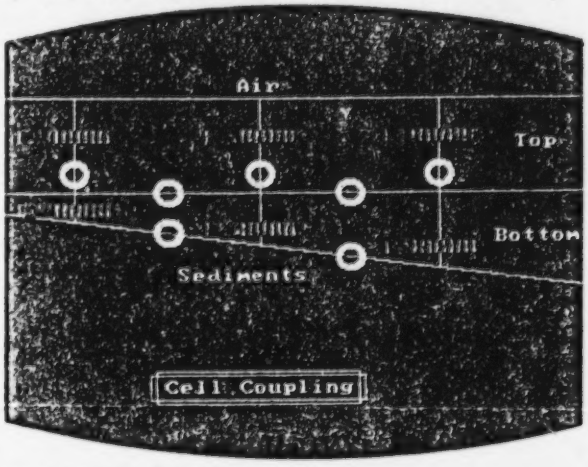
Data management. The previous

SCREEN 4
Physical, chemical, and biological processes in each model cell[a]



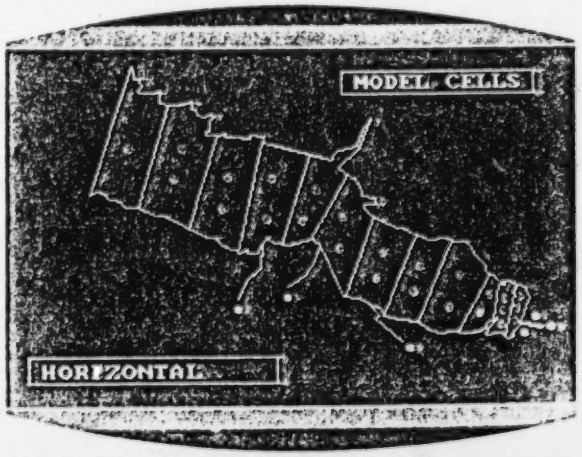
[a]Animation (moving circles and arrows) is used to represent flow and exchange processes.

SCREEN 5
A network of model cells[a]



[a]Animation (moving circles and arrows) is used to represent cell transfer processes.

SCREEN 6
Map of Green Bay[a,b]



[a]Computer map shows segmentation of model cells and locations of sampling stations.
[b]Fox River is shown at far right, not to scale.

discussion explains how the personal computer can be used to organize and illustrate the components of a large-scale water quality management project. The personal computer also can be used to store, display, and retrieve data on an interactive basis. *Option 6* from the main menu (Screen 1) contains data from experiments that define the major kinetic mechanisms in the model. *Option 7* allows the user to display system-loading data in a convenient manner. As an example, Screen 7 shows a pie chart for the total phosphorus loading into the bay from the four major tributaries. It summarizes vast quantities of data regarding the magnitude of phosphorus loading from each tributary. Such illustrations are easy to develop with BASIC and color graphics commands available on many personal computers.

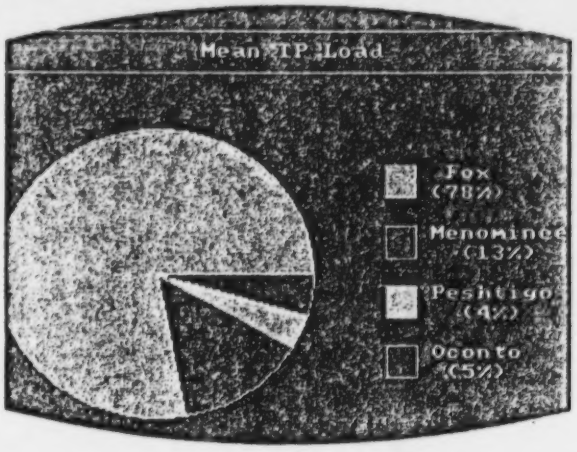
Option 8 from the main menu (Screen 1) presents the user with a submenu for model input data. All of the model coefficients, forcing functions, and calibration data can be interactively input, retained, and later retrieved from the computer using this submenu. The ability to handle data in an interactive manner is an important advantage of the personal computer in large-scale water quality management projects.

Model simulations. The personal computer can be used to compute the steady-state or time-variable concentration of pollutants in various sections of Green Bay. The steady-state concentrations are computed by solving a system of linear algebraic equations. In our case, 19 equations represent the concentrations of each variable in each model cell. There are six model variables for a total of 114 equations. These equations can be solved by a number of standard numerical techniques. We have found that the Gauss-Seidel iterative technique (*11*) is well suited for our equations when measured concentrations are used as initial guesses. Convergence to within 0.1% is usually obtained in 20–40 iterations and takes less than one min of execution time when compiled BASIC programs are run with a standard IBM PC.

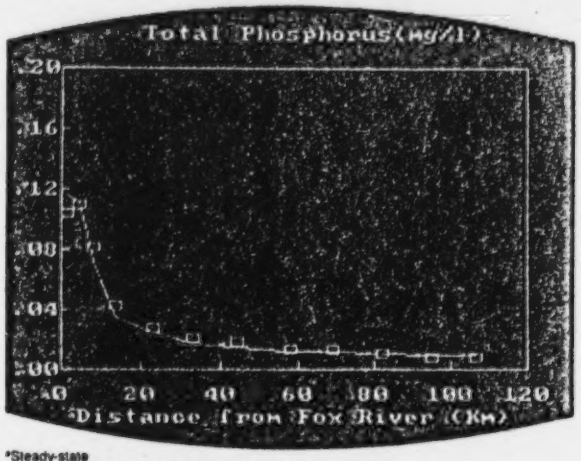
Option 9 from the main menu (Screen 1) gives a model simulation submenu. The submenu allows the user to select the variable to be computed, steady-state or time-variable concentrations, and graphic or tabular output. Screen 8 shows a computer-generated plot of measured summer average phosphorus data (represented by the small boxes) versus concentrations calculated by the model (shown as the line).

Time-variable concentrations are computed by solving a system of differential rather than algebraic equations.

SCREEN 7
Computer-drawn pie chart showing contribution by tributaries to total phosphorus load

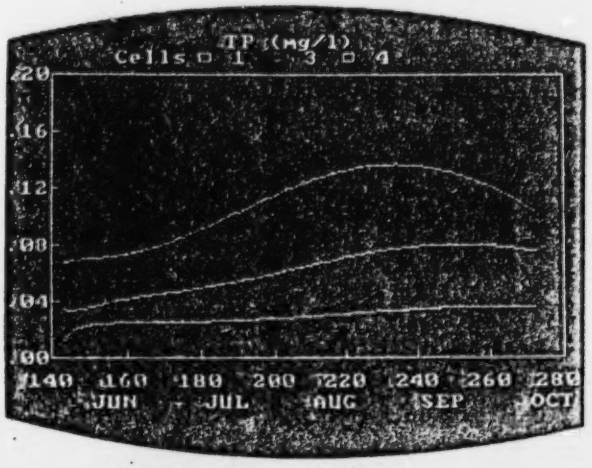


SCREEN 8
Total phosphorus concentrations[a,b,c,d]



[a]Steady-state
[b]As function of distance in Green Bay from mouth of Fox River.
[c]Small boxes represent measured summer average total of phosphorus concentration for each model cell.
[d]Line represents concentration calculated from model.

SCREEN 9
Time-variable total phosphorus concentrations[a,b]



[a]During summer for three stations in southern Green Bay.
[b]Horizontal axis represents day of the year.

The equations have time-variable coefficients and forcing functions because temperature and tributary loading vary throughout the season. The differential equations can be solved using various numerical techniques. We have found that a second-order Ralston technique (*11*) is simple to program and is sufficiently accurate when using a step-size of 0.5 day.

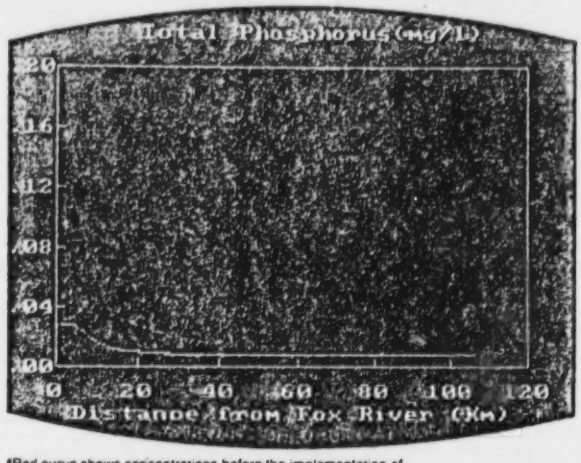
Screen 9 shows a computer-generated plot of the seasonal variation of phosphorus for the first three model cells lakeward from the mouth of the Fox River. The vertical axis represents phosphorus concentrations in mg/L; the horizontal axis represents the day of the year. We are able to compute the seasonal variation of all model variables in about 6 min using compiled BASIC programs and a standard IBM PC. Although this is satisfactory for most applications, the computation time could be reduced considerably by using a math-processing chip, a more efficient language, or more powerful hardware. Higher order mathematical techniques then may be employed with a larger step size, but these are more difficult to program. We elected to use the most basic approach because of its simplicity and widespread availability.

Management applications. *Option 10* from the main menu (Screen 1) concerns management applications. This selection allows the user to employ the personal computer to investigate interactively various management strategies or pollution abatement alternatives. The user defines new loads for the variables of interest and then returns to the main menu (Screen 1) to recompute the resultant concentration profiles. New profiles can be compared with profiles computed under current conditions to evaluate the impact of changes in system loading. For example, using *Option 10*, the total phosphorus loading from the upper Fox River was substantially reduced, simulating a hypothetical phosphorus management program; the software allowed new concentrations to be computed and compared with old concentrations.

Screen 10 shows the comparison on a plot constructed by the personal computer. The top curve represents a profile of phosphorus concentrations before a major phosphorus management program was undertaken; the bottom curve shows this profile after the program came into being.

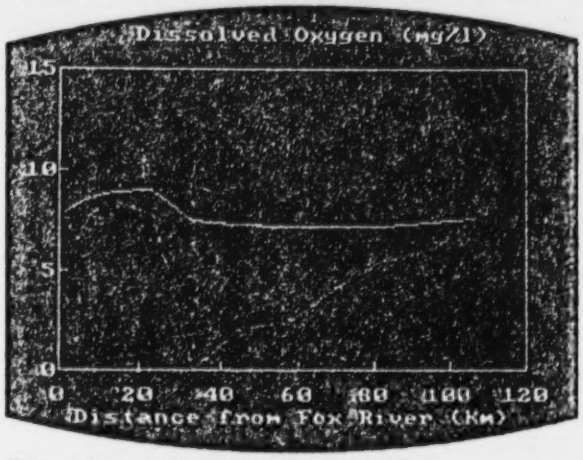
The model also may be used to evaluate the relative importance of individual biochemical rate processes by omitting the contribution of specific components in the mass balance equations. For example, when *Option 8* is chosen from the main menu, the impact of sediment oxygen demand on dissolved oxygen concentration can be examined by changing the appropriate coefficient values.

SCREEN 10
Profile of steady-state total phosphorus concentrations[a,b]



[a]Red curve shows concentrations before the implementation of a major phosphorus management program in the Fox River basin. [b]Yellow curve shows concentrations after program was implemented.

SCREEN 11
Profile of steady-state dissolved oxygen concentration[a,b]



[a]Red curve shows concentrations before the implementation of a phosphorus removal program in the Fox River basin. [b]Yellow curve shows concentration after program was implemented.

Screen 11 shows the calculated increase in dissolved oxygen (top curve) following a significant reduction in Fox River total phosphorus loads and the attendant reduction of the sediment oxygen demand to zero. The bottom curve shows the oxygen concentrations prior to the improvements.

Historically, oxygen depletion problems in Green Bay have been linked to tributary loads of oxygen-demanding substances. The simulations presented here strongly suggest that internally produced organic matter and sediment oxygen demand are the primary causes of dissolved oxygen depletion in Green Bay. They indicate that remedial measures to control total phosphorus discharges and reduce eutrophication offer the greatest opportunity for significant improvements in water quality.

These computations can be performed easily with the personal computer and the program developed for this project. The personal computer facilitates the consideration of many management alternatives on an interactive basis and enables decision makers to evaluate readily the impact of various abatement strategies on water quality.

New applications

The personal computer is becoming increasingly advantageous for modeling large systems such as Green Bay. More research will be devoted to the development of natural system models that have fewer computational demands and are more accurate and reliable. Simple models may be more reliable than needlessly complex ones, because of the uncertainties introduced with an excessive number of model coeffi-

cients. Monte Carlo techniques can be used to evaluate the performance and reliability of models of different complexity (*1*).

The convenience of personal computers and the use of simple but elegant models will facilitate the consideration of more alternatives during the design and evaluation phases of large-scale modeling projects. This will encourage more creative and holistic analysis and management activities. We will be able to communicate the results of our analyses to decision makers and to the public more effectively using graphics, animation, and the portability features of personal computers.

Overall, our experience with Green Bay and the personal computer strongly suggests that water quality modeling will play a greater role in decision making and management. In the long run, we expect to see these applications expand to larger systems as computer hardware becomes more powerful and as we become more sophisticated in our approach to model design.

Acknowledgments

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